HISTORIC AND RECENT LANDSCAPE CHANGES IN RELATION TO BEAVER ACTIVITY IN VOYAGEURS NATIONAL PARK, MINNESOTA, USA

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Introduction

Beaver (*Castor canadensis*) have the ability to significantly alter landscape structure through the creation of impoundments, here defined as wetland or open water systems created as beaver dams obstruct the flow on low-gradient streams (Collen & Gibson 2001,Wright *et al.* 2002). These landscape changes have wide-ranging effects, from influences on fish populations (Snodgrass & Meffe 1998,Schlosser & Kallemeyn 2000) to watershed biogeochemistry (Naiman *et al.* 1994). The proportion of the landscape in impoundments fluctuates with beaver populations, and declines in populations result in the natural succession of impoundments from open-water systems to other wetland types. The dynamics of beaver pond creation and abandonment were the subject of a series of seminal landscape ecology studies in the late 1980s and early 1990s (Naiman *et al.* 1988,Johnston & Naiman 1990a,Johnston & Naiman 1990b,Pastor *et al.* 1993). These works were based largely on the interpretation of aerial photography to delineate the various wetland types associated with beaver activities (Johnston & Naiman 1990b). Historic patterns of beaver impoundments within the Kabetogama Peninsula were delineated from six aerial photo sets spanning 46 years: 1940, 1948, 1961, 1972, and 1986 (Johnston & Naiman 1990a,Johnston & Naiman 1990b). Geographic information system technologies, newly adopted by ecologists (Johnson & Host 2010), were used to answer ecological questions related to the ecosystem engineering abilities of beavers, such as the rate of impoundment creation and expansion in relation to beaver population dynamics and the distribution of seral stages of beaver-related impoundments (hereafter impoundments) across the landscape. In a parallel study, Broschart and colleagues used MN DNR transect surveys to develop a model predicting beaver colony abundance from the proportions of wetland types on the Kabetogama Peninsula (Broschart *et al.* 1989). These studies illuminated the extensive impact beavers can have on boreal landscapes, demonstrating that beavers were responsible for significant land cover changes over 15% of the Kabetogama landscape in a 50-year span.

Beaver colony density on the Kabetogama Peninsula has fluctuated annually but has been consistently very high over an extended period from the late 1970s through the late 1990s. This period of high beaver abundance was concurrent with the availability of 10-30 year-old aspen (*Populus* spp.) and white birch (*Betula papyrifera*) regenerated after the last significant logging of the 1950s and 1960s. However, no significant forest disturbance has occurred on the Kabetogama Peninsula since the late 1960s and a significant beaver population decline has been anticipated for some time in response to declining foraging habitat quality (S. Windels, pers. comm.). Recent transect surveys, remote sensing data, and field observations suggest that beavers are entering a decline phase, with some recent index values at nearly 50% of the long-term average (S. Windels, unpubl. data). Anticipated land cover changes associated with a declining beaver population in an area with limited food resources include a decrease in open-water ponds and shallow marshes and an increase in seasonally flooded meadows (Broschart *et al.* 1989). Our objective for this project was to update the published work of Johnston and colleagues by assessing changes in wetland type and area using more recent (1997-2005) aerial photography. A second objective was to relate these changes to beaver population data recorded in aerial surveys during a period of potential beaver population decline.

Methods

Study Area

This study was conducted on the Kabetogama Peninsula in Voyageurs National Park at the US/Canadian border in northern Minnesota (Figure 1). The peninsula is predominantly boreal forest, dominated by trembling aspen (*Populus tremuloides*), paper birch (*Betula papyrifera*), balsam fir (*Abies balsamea*) and white spruce (*Picea glauca*). The bedrock-controlled topography of the peninsula is complex, resulting in numerous interspersed wetlands and lakes throughout the upland forest matrix. Beavers have been historically abundant in this area, and over time amount and types of wetlands on the peninsula have shown significant temporal variation related to patterns of beaver colonization, use and abandonment (Johnston and Naiman 1990a). The analyses for this report were conducted within the 250-km^2 Shoepack drainage basin described in Johnston *et al.* 1990a; this area comprises the eastern 85% of the peninsula, all occurring within St. Louis Co., MN (Figure 1). Mean annual temperature at International Falls, MN (40km WNW) is 2.8 deg C, and mean annual precipitation received is 62cm, of which 30% is snow (NOAA 2010).

Delineating Beaver Impoundments

Previous studies resulted in the creation of classified aerial photos/mosaics for the Kabetogama Peninsula from 1940 through 1986 (Table 1). This time series was extended by photo-interpreting beaver-related impoundments from orthorectified photo sets dated 1997 (color infrared), 2003 (true color) and 2005 (color infrared; Table 1). Imagery was scanned at 800 dpi and georectified (i.e., matched to a set of geographical coordinates so that each pixel of the image is assigned a coordinate) using the *Imagewarp* utility in the Arcview Geographic Information System software (ESRI 1992). To maintain acceptable levels of accuracy, we used a minimum of 15 control points per image, with a target RMS error of 1 m. The RMS error measures the differences between the control points on the image compared with the projection of those points onto ground space (Morad *et al.* 1996).

Impoundments were delineated by digitizing boundaries on-screen using ArcView (ESRI 1992). The digitizing environment included previously classified photos and other imagery as background layers; further comments on methodologies for impoundment classification appear in Appendix A. Beaver impoundments ranging from-open water ponds to beaver meadows were delineated on-screen and classified based on the US Fish and Wildlife Service wetland and deepwater habitat classification (Cowardin *et al.* 1979). For comparison with Johnston and Naiman (1990a,b), classes were collapsed into broader wetland, vegetation, and hydrologic classes (Table 2).

Comparison of Digitizing Methods

The Johnston and Naiman (1990*a,b*) delineations of beaver impoundments were based on unrectified aerial photographs. Linework for the impoundments were delineated with marker on mylar overlays and transferred to 1:24,000-scale USGS topographic maps using a Zoom Transferscope (Sokkisha, Tokyo, Japan). Polygons were converted to grids (7 x 7 m resolution) for analysis. Our method (on-screen digitizing [OSD]) differed from the zoom transfer method (ZTM) used in Johnston and Naiman (1990b) in that impoundments were delineated on previously rectified photographs, and analyzed in a vector environment. There are several reasons that comparisons between the 1940-1986 and 1997-2005 data sets might be confounded: marker line width, distortions in linework created by the zoom-transfer process, differences in visible features between digitizing directly from the actual 9x9 inch photos as opposed to working with high-resolution scans magnified onto a high-resolution monitor, and differences in interpreter experience. For those reasons, we tested for differences between the two interpretation periods by redigitizing portions of 1990 color IR air photos from the MN DNR using the OSD approach. The objective of this comparison was to determine if there were systematic biases between the ZTM and OSD methods that would warrant development of a correction factor to facilitate comparisons between time periods.

To test for differences, ten random points were selected across the peninsula and used as the centers for 1-km^2 (564-m radius) circular plots. The 1 km^2 area is approximately twenty times larger than the largest average beaver pond size (4.7 ha) reported by Johnston and Naiman (1990*a*), and the total area sampled by the 10 plots represents 4% of the 250-km^2 study area (Johnston and Naiman 1990*a*). Several selection criteria were established for plots to be included in the sample: acceptable center points were at least 564 m from the shoreline of the peninsula (to ensure that the entire area of each circle fell within our domain of interest), had less than 40% open water, had no overlap with other plot areas, and, to avoid photo-edge effects, were contained completely within single photos. A randomized list of 24 candidate plots was created, and individual airphotos were assessed to determine if plots met the selection criteria. If a plot did not meet the criteria, it was removed from the list and the next plot considered; this process was repeated until the pool of 10 plots was complete (Figure 2).

Beaver ponds for the 1990 photos were delineated using the on-screen digitizing methods employed for the 1997 through 2005 photo sets. A paired *t*-test was used to compare key metrics of impoundments (e.g., total and mean area and number of impoundment types) using ZTM and OSD methods. We also visually inspected the plots on the rectified images to determine potential sources of discrepancies between the two interpretations.

Spatial analyses

Patch metrics, including total, mean and median areas, numbers, and types of beaver impoundments in each wetland class were summarized for the 1997-2005 photo sets. Impoundments were summarized using the impoundment types defined in Johnston & Naiman (1990a), as well as by their broader vegetation (bog, herbaceous, deciduous forest, open water) and hydrologic classes (moist, wet, ponded; Table 2). Variation in patch size within impoundment types was described by standard deviations, coefficients of variation, and percentiles.

Specific transitions in impoundment classes were calculated between the 1997 and 2005 datasets. The ARCMAP *Identity* function (ESRI 1992) was used to intersect maps from the two time periods. This function creates a new data layer that maintains the identities of all polygons and attributes from the intersected layers. From this composite dataset, it is possible to determine if and how each polygon changed between the two time periods. The end product is a transition matrix with a tabulation of the numbers of hectares that changed impoundment classifications (also expressed as % change).

Comparisons of Impoundment Type with Beaver Survey Data

Spatial data on impoundment type and area were compared with two sources of beaver population data. The National Park Service provided a GIS database of beaver cache locations recorded during aerial beaver surveys in 1984 and 2000. A point-in-polygon analysis was conducted to associate cache locations with wetland type. The years that caches were surveyed, however, did not correspond to the years that photographs were interpreted. Caches were associated with the 1988 and 2003 impoundment classifications, and counts of caches were tabulated by impoundment type. We acknowledge the potential error related to the fact that impoundments may have changed over the 3-4 year interval between the cache survey and dates of imagery.

Changes in impoundment class were correlated with changes in an index of beaver colony density (# caches/km) recorded during aerial transects conducted by the MN Department of Natural Resources and Voyageurs National Park between 1958 and 2005. Each year's observations typically consisted of 11 transects with an average transect length of 8.1 km, for a total of 88.6 km surveyed. Flights were conducted in 1958, 1961, 1964, 1968-1996, 1998-2002, and 2005. We used regression analyses to correlate the colony density index with areas in different impoundment types. Indices were interpolated to estimate values for 1997 and 2003, during which beavers were not surveyed.

Broschart *et al*. (1989) used the above data to develop models to predict a beaver colony density index (# caches/km of survey route); the best predictors were *proportion of shallow marsh* and *proportion of shallow marsh+seasonally flooded impoundments*. We applied these models to our study area and evaluated the predictions against the sequence of aerial observations and changes in landscape structure.

Results and Discussion

Comparison of Digitizing Methods

The comparison of ten 100-ha circular plots showed that impoundments delineated using on-screen digitizing were similar to those produced by the zoom-transfer process (Figures 3, 4). Plot 5, for example, is one of the more divergent plots between the two methods, and provides an example of these similarities and differences (Figure 5). The lower image, with linework only, shows the general similarity in linework, generally capturing the outlines of the impoundment complex. The upper figure shows a misalignment of the riverine feature in the upper part of the plot in the ZTM linework, characteristics of lines transferred from non-rectified imagery. The OSD linework shows a close relationship to boundaries on the underlying photograph. Also, the ZTM linework has fewer vertices, resulting in a coarser, more generalized outline of the impoundments. Finally, while the overall areas of impoundment were similar, the OSD delineated more individual impoundments than the ZTM delineation. The ability to scan photographs at high resolution and magnify them onto a large screen monitor allows the interpreter to see considerably more detail (Figure 5). Note in this figure that the ZTM interpretation generalized a large polygon as Wet Meadow – subsequent interpretation with OSD subdivided this into three other impoundment types.

There were no statistically significant differences in numbers of impoundments or total or average impoundment areas. The differences in total impounded area within the 100 ha plots mapped between the zoom-transfer (ZTM) and on-screen digitizing (OSD) ranged from -3.8 to 5.9 ha, with 6 of 10 samples overestimated with ZTM (Table 3). The average difference between methods was 0.43 ha (16.65 ha with ZTM vs 16.22 with OSD), with ZTM identifying a marginally greater area than OSD methods. A paired *t*-test for differences in total area was not significant ($p=0.60$). Mean impoundment sizes (0.9 ha OSD, 1.1 ha ZTM) were also not significantly different between digitizing methods ($p=0.07$). Finally, the number of impoundments ranged from 11-29 in the ZTM and 8-38 in the OSD, with average numbers of 16.7 and 19.1 respectively; means were not significantly different ($p=0.19$). As a result, the lack of systematic bias between ZTM and OSD methods indicates that adjustment of impoundment numbers or area is not necessary for comparing earlier efforts with interpretations from the present study.

Landscape Changes in Impoundment Type, Hydrology, and Vegetation

Johnston and Naiman (1990b) reported a dramatic increase in the total area of beaver impoundment from 1% of the peninsula in 1940 to 13% in 1986. The impoundment area increased from 3196 ha in 1986 to 3234 ha in 1997. Total impoundment area was quite stable between 1997 and 2005 (Figure 6).

While the total impounded area remained relatively constant from 1986-2005, there were strong shifts in wetland type, which were in turn reflected by changes in hydrologic and vegetation classes. These shifts provide evidence that the level of beaver activity has decreased, resulting in landscape-scale changes in hydrology and dominant plant cover. The area of pond/deep marsh showed the greatest increase among all impoundment types through 1986, but dropped from its maximum of 873 ha in 1986 to 485 ha in 1997 and 469 ha in 2005 (Figure 6). These levels are lower than any observed in the previous 44 years in the Kabetogama Peninsula. Conversely, the wet-meadow class showed a strong increase from 616 ha in 1986 to 1076 ha in 2005. The floating meadow class also showed a strong proportional increase from 164 ha in 1986 to 317 ha in 2005. The replacement of pond and deep-marsh types with wet and floating meadows is consistent with landscape patterns observed during a decline in beaver population and patch abandonment (Wright *et al.* 2009). Example time sequences showing changes in impoundment type are presented in Appendix A.

Johnston and Naiman (1990a) reported relatively consistent mean "pond-site" areas across their study period, with pond-sites defined as including "…all areas with vegetation altered by the past or present ponding of water by beaver, and ranged from ponds to beaver meadows, which are formerly inundated areas that have revegetated to grass and sedge meadows". They further note, however, that new impoundments created after 1972 had significantly reduced areas (mean ~1.3 ha between 1972 and 1986 vs. 3.6 ha between 1940 and 1961).

In our study, most mean impoundment areas (which are not directly comparable, and mostly likely smaller than the pond-sites reported in Johnston & Naiman 1009a) remained in the 1- to 2-ha size classes between 1997-2005, with values somewhat lower in 2005 (Table 4). But the standard deviations around mean patch area were high, and all coefficients of variation were > 1.0, indicating high variance in the size class distribution of individual patches. In most cases, the means were skewed upward by the inclusion of a few large patches in a distribution consisting of many small patches (Table 4). For this reason, we report medians and quartiles in Table 5. Median patch values were considerably less (Table 5), ranging from 0.2 to 2.1 ha. Saturated bogs (75th percentile > 4 ha) and flooded bogs (75th percentile > 2.3 ha) were consistently the largest patches observed, and saturated bogs increased in median patch size from 1.9 to 2.1 ha between 1997 and 2005. Deep ponds (i.e., Pond,Deep Marsh type), which experienced an overall sharp reduction in total area, showed a small decrease in median patch size from 0.32 to 0.22 ha. From a landscape-structure perspective, the decrease in impoundment patch size is consistent with the observations of changes from shifts from larger open-water systems to less hydric impoundment types associated with reduced dam maintenance and lowered water levels.

The total numbers of impoundments fluctuated over the three time periods, decreasing from 2603 in 1997 to 2372 in 2003, and then increasing to 2947 in 2005. Note also that total impoundment area also showed a slight decrease in 2003, a drought year (43 cm total precipitation; National Weather Service 2009). Johnston and Naiman (1990b) reported a steady increase in numbers of impoundments between 1940 and 1986; they summarized their data by 'pond-sites', however, and those data are not directly comparable to the individual impoundment data reported here.

A broader picture of landscape change may be obtained by grouping wetland classes into dominant vegetation types: open water, bog, herbaceous, or woody deciduous cover (Figure 7). Johnston and Naiman (1990b) note that the proportion of flooded deciduous and bog types decreased from 50% of impoundments to 29% in 1986 – this proportion has remained relatively stable through 2005. The area of open water, however, has decreased from its 1986 maximum of 873 ha to 485 ha in 1997 and 469 ha in 2005 (Figure 7). Replacement has been predominantly by impoundment types dominated by herbaceous cover; these have increased 25% in area over the 1986 values (Figure 7).

A hydrological classification of impoundment types shows that while the total impoundment area has remained relatively stable since 1986, the hydrology has shifted from open pond conditions to the moist soil conditions characteristic of wet meadows and seasonally flooded impoundments (Figure 8). The increasing ponded area that continued through 1986 (Johnston & Naiman 1990b) dropped 22% to about 1,100 ha by 1997. Between 1986 and 1997, about 417 ha or 30% of the total 1986 pond area shifted into the 'moist' hydrologic categories, which includes wet meadows, wet deciduous shrubs, and saturated bogs and forest (Figure 8). This shift from open water to wet vegetated systems appears to indicate a landscape-scale successional trend that might follow reductions in beaver activity (Sturtevant 1998).

Landscape Transitions

In addition to general summaries of changes in impoundments, we calculated specific transitions for individual polygons between 1997 and 2005. In general, impoundments were relatively stable over this time period - 80 to 90% of impoundments remained in the same wetland class. The dominant (> 20 ha) transitions that occurred between 1997 and 2005 were as follows (full transition matrix presented in Table 6):

- Transitions to drier types
    - Floating Meadow to Saturated Deciduous Forest (69 ha)
    - Ponds to Floating Meadow (63 ha)
    - Ponds to Saturated Deciduous Forest (32 ha)
    - Floating Meadow to Shallow Marsh (26 ha)
    - Shallow Marsh to Saturated Deciduous Forest (23 ha)

- Transitions to wetter types
    - Floating Meadow to Pond (40 ha)
    - Saturated Deciduous Forest to Shallow Marsh (36 ha)
    - Shallow Marsh to Floating Meadow (36 ha)
    - Saturated Deciduous Forest to Floating Meadow (35 ha)
    - Saturated Deciduous Forest to Deep Pond (27 ha)

Overall, 236 ha of impoundments moved into drier categories and 150 ha moved into more hydric types. This latter case may indicate a reflooding or reoccupancy of older pond sites. The transitions to wetter or dryer types appear to be evenly dispersed across the peninsula, and many of the large complexes of impoundments show both types of change (Figure 9).

Comparisons with beaver population data

The aerial surveys conducted by the MNDNR/VNP provide a near-continuous index of beaver abundance from 1960 through 2005 for the Kabetogama Peninsula The surveys document the dramatic increase in beaver abundance through the ~1981, a period of relatively stable population between from 1981-1994, followed by a period of unstable population decline through 2005 (Figure 10). The analyses showed a positive but not statistically significant ($p=0.05$) relationship between cache density and area in deep ponds ($r^2 = 0.48$, $p = 0.08$). Relationships between beaver abundance and area in shallow marshes showed a weak positive trend and area in wet meadows a weak negative relationship ($r^2 < 0.30$); neither trend was statistically significant.

It is not surprising that relationships of cache densities with impoundment areas in the same year are not strong; hydrologic changes and the associated vegetation responses occur slowly, and one would expect a lag between pond abandonment and changes to impoundments. The deep pond area, which showed the strongest correlation with cache density, tracks the trend in beaver population rise and decline rather well. Shallow marsh area shows an interesting trend: the peak in shallow marsh area (558 ha) occurred in 1981, about the time that the beaver population reached a high and relatively stable plateau (Figure 10). Shallow marsh area dropped to 476 ha in 1986 (Johnston & Naiman 1990a) and has been relatively stable around 308 ha between 1997 and 2005. The decline in shallow marsh thus appears to be in advance of the beaver population decline, which began in the mid-1990s (Figure 10). The other significant landscape change that occurred throughout the time sequence but increased in the 1997 period is the strong increase in wet meadows, one of the later successional endpoints associated with declines in beaver populations (Sturtevant 1998).

In addition to the MN DNR flights, the National Park Service conducted aerial beaver censuses for the Kabetogama Peninsula in 1984 and 2000. There was no difference in the numbers of active beaver lodges (i.e., lodges with caches) observed in the two time periods; both surveys recorded 253 caches (Figure 11). There was a pronounced shift in active beaver lodges associated with drier wetland types between 1984 and 2000 (Figure 12). While this pattern is consistent with other patterns we observed, it is likely an overestimate of the true proportion of active beaver lodges associated with drier types in 2000 vs. 1984 because 2003, the year of aerial photography, was a considerably drier year than 2000.

As noted in Broschart *et al*. (1989), the shift toward seasonally flooded meadows is an indicator of hydrologically lower water conditions, and is potentially related to a decline in beaver populations, with subsequent dewatering of impoundments as dams are no longer maintained. We applied our data to Broschart's one- and two-factor models for predicting beaver colony density. The single-factor model, based on proportion of shallow marsh, underestimated observed cache densities (Table 7). The two-factor model, which adds a negative weight based on the proportion of seasonally flooded meadows, produced estimates < 0. This latter artifact is likely due to the fact that the proportion of wet meadows in the 1997-2005 period was much higher than any values used when the model was developed. Broschart *et al*. (1989) note that the model was developed using data from a time of increasing populations, and needs to be tested under stable or declining population conditions – the present results indicate that the model is not applicable to conditions outside the range of model development.

Summary

Beaver effects on the landscape are long-lasting. The total area in beaver-related impoundments on the Kabetogama Peninsula rose sharply from ~250 to 2500 ha between 1940 and 1960. A slower rate of increase was observed from 1961 to 1986, reaching 3,196 ha. The present data indicates that between 1997 and 2005 the total impounded area has remained quite stable at 3233 +/- 5 ha (mean ± 1 standard deviation). While the total area has remained relatively consistent, the dominant wetland types have changed dramatically. The amounts of pond/deep marsh have declined by 46% from 1986 levels. The area in wet meadow has increased by 75% over 1986 levels, and now accounts for about one third of the total impounded area. An analysis of spatially-explicit transitions between impoundment types showed that, in general, open water impoundments are succeeding to hydrologically drier types, such as floating meadows and saturated deciduous forest. The largest in-place transitions were from floating meadow to saturated deciduous forest. Some of these changes may be due, in part, to shifts in precipitation and groundwater, which were beyond the scope of this study. The collective work of Johnston and Naiman, however, attributes the large-scale changes observed in VNP over 45 years to beaver activity, and the present work supports the concept of a natural succession of wetland vegetation types related to changes in beaver populations. With the exception of the position of lines delimiting open water from emergent vegetation, we believe water level effects are small compared to wetland response to beaver colonization and abandonment.

The trend toward smaller patch sizes reported by Johnston & Naiman (1990a) continued in the present study. Johnston and Naiman (1990a) note that the area of newly created deep ponds showed a steady decrease from 3.7 ha in 1948 to 1.2 ha in 1986. Mean size of extant patches of deep ponds in 2005 was 0.63ha, suggesting that new ponds since 1986 are at least smaller than 1.2ha. The largest patch sizes remain in the saturated bog and flooded bog impoundment types, 3.2 and 2.3 ha respectively.

The long-term beaver abundance index show that beaver populations in 2005 are at their lowest level since 1973. Values for 2007 and 2009 were higher than 2005, but still 25-40% lower than the 1980-1990 peak levels (S. Windels, VNP, pers. comm.) A population increase noted from 2000-2002 was not well correlated with landscape changes, but the general patterns of impoundment change are consistent with a declining beaver population – the area in deep pond tracked population changes rather well and the proportion of wet meadows increased steadily over the course of the study. The total area of open water in 2005 was lower than at any point since the 1950s – this corresponds to a 50% decline in beaver abundance since mid-1990s population plateau. The reduction in areas of shallow marsh occurred in advance of the population decline; there are numerous possible explanations for this, including potential beaver exploitation of a suboptimal landscape.

There are several caveats to consider in interpreting the data and results of this study. The type and resolution of imagery varied both within periods and between the early work (1940-1986 photographs) and the 1997-2005 periods. We were fortunate to have one of the same interpreters (Paul Meysembourg) from the Johnston and Naiman work conduct the 1997-2005 interpretations, but there was still a 15+ year difference in the timing of interpretations. In addition, there was a strong difference in technology, including the use of georectified imagery in the recent work, and a vastly improved GIS environment, in terms of both monitor resolution and tools for using ancillary data, comparing images, and digitizing linework. The question of how the magnitude of differences related to improved imagery, technology, and different interpretation episodes compares with the magnitude of real changes in the VNP landscape is an important one. Our additional study to compare zoom-transfer and on-screen technologies inherently included interpreter and digitizing environment differences. In that analysis, the mean difference in total impounded area was 0.4%, compared with an overall increase of 3.1% in impoundment area across the study area between 1986 and 1997. Similarly, the differences in mean patch area from the ZTM/OSD analysis was 0.2 ha. Therefore while there are certainly imperfections in integrating these two different studies, we believe the patterns of landscape change reported here represent real trends in impoundment area and types. The changes in total and mean impoundment areas were smaller in the 1997-2005 analysis, but these interpretations were consistent in terms of the interpreter and methods used.

The multiple lines of evidence from trends in impoundment type, patch structure, and location of caches support the conclusion that beaver activity on the Kabetogama Peninsula is on the decline, resulting reduced dam maintenance and abandonment of ponds. This in turn results in an alteration of hydrologic regimes toward drier conditions: the drainage of ponds results in a succession toward flooded or saturated marshes and saturated deciduous forest. Throughout its relatively short history, Voyageurs National Park has been recognized for its diversity and abundance of beaver-related habitats. The landscape trends reported here will contribute significantly to the future management of the park, including fire management, interpretation, and conservation and management of wetland-dependent species and communities.

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Table 1. Attributes of historic and recent aerial photographs from Voyageurs National Park. 1940-1986 data from Johnston and Naiman 1990b, 1997-2005 from present study.

Year of image	Film type	Method of photo-interpretation	Scale or Resolution (m)	Spatial extent (county)	Commissioning Agency
1940	BW panchromatic	zoom-transfer	1:20,000	St. Louis+Kooch	U.S. Agric. Stabilization & Conservation Service
1948	BW IR	zoom-transfer	1:15,840	St. Louis	Boise-Cascade Company
1961	BW IR	zoom-transfer	1:15,840	St. Louis+Kooch	St. Louis County
1972	BW IR	zoom-transfer	1:15,840	St. Louis	Voyageurs Nat. Park
1981	True color	zoom-transfer	1:24,000	St. Louis	Superior National Forest
1986	Color IR	zoom-transfer	1:24,000	St. Louis+Kooch	Natl Science Foundation
1997	DNR IR	onscreen digitizing	1:15,840; .5m	St. Louis+Kooch	MN DNR
2003	True color	onscreen digitizing	2m	St. Louis+Kooch	USDA Farm Service Agency (FSA/NAIP)
2005	DNR IR	onscreen digitizing	.5m	St. Louis	MN DNR

Table 2. Classification of USFWS Wetland Classes (Cowardin 1979) into generalized wetland, vegetation and hydrologic classes.

USFWS Wetland Class	Wetland Class	Vegetation Type	Hydrologic Class
SS5E	Dead Woody	Deciduous	Pond
SS5F	Dead Woody	Deciduous	Pond
FO5E	Dead Woody	Deciduous	Pond
FO5F	Dead Woody	Deciduous	Pond
SS1B	Wet Deciduous Shrubs	Deciduous	Pond
EM1Fm	Floating Meadow	Herbaceous	Pond
SS1Fm	Floating Woody Mat	Bog	Pond
SS3Fm	Floating Woody Mat	Bog	Pond
SS8Fm	Floating Woody Mat	Bog	Pond
XXXFmc	Floating Woody Mat	Bog	Pond
F08Fm	Floating Woody Mat	Bog	Pond
FO5Fm	Floating Woody Mat	Bog	Pond
SS5Fm	Floating Woody Mat	Bog	Pond
SS3E	Flooded Bog	Bog	Wet
SS8E	Flooded Bog	Bog	Wet
XXXEc	Flooded Bog	Bog	Wet
FO8E	Flooded Bog	Bog	Wet
FO8F	Flooded Bog	Bog	Wet
FO1F	Flooded Deciduous	Deciduous	Wet
SS1F	Flooded Deciduous	Deciduous	Wet
XXXFc	Flooded Deciduous	Deciduous	Wet
UBF	Pond, Deep Marsh	Open water	Pond
UBH	Pond, Deep Marsh	Open water	Pond
AB3F	Pond, Deep Marsh	Open water	Pond
SS3B	Saturated Bog	Bog	Moist
SS8B	Saturated Bog	Bog	Moist
XXXBc	Saturated Bog	Bog	Moist
FO8B	Saturated Bog	Bog	Moist
FO8A	Saturated Bog	Bog	Moist
FO1A	Saturated Deciduous Forest	Deciduous	Moist
FO1E	Saturated Deciduous Forest	Deciduous	Moist
EM1F	Shallow Marsh	Herbaceous	Wet
SSlE	Wet Deciduous Shrubs	Deciduous	Moist
EM1E	Wet Meadow	Herbaceous	Moist
EM1B	Wet Meadow	Herbaceous	Moist
EM1A	Wet Meadow	Herbaceous	Moist
US4A	Wet Meadow	Herbaceous	Moist
FO5B	Wet Meadow	Herbaceous	Moist
Lake	Not Impounded Lake	Water	Water
Upland	Not Impounded Upland	Land	Land
Not Impounded	Not Impounded Upland	Land	Land

Table 3.1 Percent area within 100 ha plots classified as impounded using zoom-transfer and onscreen digitizing methods.

Plot	Zoom Transfer	Onscreen Digitizing	Difference in % impounded area
1	9.23	9.10	0.13
2	25.16	25.54	-0.38
3	11.88	5.95	5.93
4	10.67	10.20	0.48
5	21.74	25.58	-3.84
6	13.01	10.78	2.23
7	11.82	11.42	0.40
8	15.86	16.34	-0.48
9	23.24	22.41	0.84
10	23.91	24.89	-0.98
Average	16.65	16.22	0.43
StDev			2.48

Table 3.2 Mean areas of individual impoundments in 100 ha plots using zoom-transfer and onscreen digitizing methods.

Plot	Zoom Transfer (ha)	Onscreen Digitizing (ha)	Difference in mean area (ha)
1	0.71	1.01	0.30
2	1.14	1.06	-0.08
3	0.99	0.74	-0.25
4	0.53	0.60	0.07
5	1.98	1.16	-0.81
6	0.87	0.63	-0.23
7	0.70	0.63	-0.06
8	1.06	0.74	-0.31
9	1.79	1.40	-0.39
10	0.82	0.65	-0.17
Average	1.06	0.86	-0.19
StDev			0.30

Table 3.3 Numbers of impoundments in 100 ha plots using zoom-transfer and onscreen digitizing methods.

Plot	Zoom Transfer	Onscreen Digitizing	Difference in number of impoundments
1	13	9	-4
2	22	24	2
3	12	8	-4
4	20	17	-3
5	11	22	11
6	15	17	2
7	17	18	1
8	15	22	7
9	13	16	3
10	29	38	9
Average	17	19	2
StDev			5

Table 4. Patch metrics for wetland classes digitized from 1997-2003 aerial photographs, Kabetogama peninsula, Voyageurs National Park.

Mean patch area (ha)			
Wetland Type	1997	2003	2005
Dead Woody	1.32	1.31	1.13
Floating Meadow	1.31	1.60	0.99
Floating Woody Mat	1.39	1.45	1.42
Flooded Bog	2.51	2.25	2.19
Flooded Deciduous	0.76	0.76	0.65
Pond, Deep Marsh	0.79	0.87	0.63
Saturated Bog	3.09	3.18	3.27
Saturated Deciduous Fore	0.90	0.90	0.84
Shallow Marsh	1.36	1.67	1.53
Wet Deciduous Shrubs	0.87	0.87	0.73
Wet Meadow	1.53	1.72	1.40
Grand Mean	1.24	1.37	1.10

Std. Deviation Patch Area (ha)			
Wetland Type	1997	2003	2005
Dead Woody	2.10	2.09	1.97
Floating Meadow	2.12	2.48	2.10
Floating Woody Mat	1.91	1.94	1.86
Flooded Bog	3.40	3.23	3.26
Flooded Deciduous	1.05	1.04	0.95
Pond, Deep Marsh	1.20	1.22	1.05
Saturated Bog	3.61	3.67	3.70
Saturated Deciduous Fore	1.42	1.43	1.40
Shallow Marsh	1.97	2.09	3.04
Wet Deciduous Shrubs	2.25	2.29	2.12
Wet Meadow	2.98	3.23	2.76

Coefficient of Variation			
Wetland Type	1997	2003	2005
Dead Woody	1.59	1.59	1.74
Floating Meadow	1.62	1.56	2.13
Floating Woody Mat	1.37	1.34	1.31
Flooded Bog	1.35	1.43	1.49
Flooded Deciduous	1.37	1.37	1.47
Pond, Deep Marsh	1.52	1.40	1.65
Saturated Bog	1.17	1.15	1.13
Saturated Deciduous Fore	1.58	1.59	1.66
Shallow Marsh	1.45	1.25	1.99
Wet Deciduous Shrubs	2.60	2.63	2.90
Wet Meadow	1.95	1.89	1.97

Number of patches			
Wetland Type	1997	2003	2005
Dead Woody	80	85	89
Floating Meadow	246	170	321
Floating Woody Mat	54	54	63
Flooded Bog	40	41	39
Flooded Deciduous	141	138	166
Pond, Deep Marsh	611	560	739
Saturated Bog	106	105	101
Saturated Deciduous Fore	149	145	175
Shallow Marsh	215	175	199
Wet Deciduous Shrubs	273	259	286
Wet Meadow	688	640	769
Grand Total	2603	2372	2947

Table 5. Median and inner and outer quartiles of wetland area (ha)

	1997				2003				2005	
Wetland Type	Median	25th	75th	Median	25th	75th		Median	25th	75th
Dead Woody	0.64	0.35	1.30	0.57	0.33	1.30		0.53	0.29	1.12
Floating Meadow	0.61	0.25	1.55	0.69	0.34	1.79		0.36	0.14	0.95
Floating Woody Mat	0.63	0.23	1.82	0.66	0.23	1.82		0.64	0.25	1.84
Flooded Bog	1.41	0.83	2.57	1.29	0.62	2.40		1.29	0.63	2.30
Flooded Deciduous	0.37	0.24	0.88	0.38	0.23	0.89		0.36	0.19	0.70
Pond, Deep Marsh	0.32	0.11	0.94	0.39	0.14	1.07		0.22	0.08	0.73
Saturated Bog	1.88	0.72	4.03	1.90	0.71	4.29		2.10	0.78	4.34
Saturated Deciduous	0.42	0.22	0.90	0.42	0.22	0.90		0.38	0.18	0.86
Shallow Marsh	0.71	0.32	1.56	0.95	0.53	2.13		0.71	0.31	1.62
Wet Deciduous Shrut	0.36	0.16	0.75	0.35	0.17	0.79		0.29	0.14	0.70
Wet Meadow	0.69	0.32	1.56	0.76	0.35	1.81		0.57	0.24	1.42

Table 6. Spatially-explicit transitions among beaver impoundment classes from 1997 to 2005 (ha).

	To Impoundment Type											
From Impoundment Type	Dead Woody	Floating Meadow	Floating Woody Mat	Flooded Bog	Flooded Deciduous	Not Impounded Upland	Pond, Deep Marsh	Saturated Bog	Saturated Deciduous Forest	Shallow Marsh	Wet Deciduous Shrubs	Grand Total
Dead Woody	242	2	0	0	1	0	6	4	23	1	0	280
Floating Meadow	4	239	4	1	1	0	40	0	69	26	1	385
Floating Woody Mat	0	1	67	0	0	0	13	0	0	0	0	81
Flooded Bog	0	4	0	95	0	0	1	1	11	0	0	114
Flooded Deciduous	2	4	0	0	99	0	4	2	3	2	0	116
Not Impounded Upland	0	0	0	0	0	81	0	0	0	0	1	84
Pond, Deep Marsh	7	63	16	0	3	0	419	1	32	14	2	557
Saturated Bog	0	2	0	14	1	0	1	373	5	0	0	397
Saturated Deciduous Forest	16	35	1	1	7	0	27	5	1210	36	2	1339
Shallow Marsh	4	36	5	2	2	0	16	0	40	269	0	374
Wet Deciduous Shrubs	1	1	0	0	0	1	1	3	11	7	135	159
Grand Total	277	388	93	114	113	82	528	388	1406	356	142	3887

Table 7. Predicted cache density index based on Broschart 1989 model, 1940-1986 as published in Broschart 1989, 1997-2005 from present study. The observed cache densities from Mn DNR aerial sampling.

Year	Predicted Cache Density - one component model (# caches/ km surveyed)	Predicted Cache Density - two component model (# caches/ km surveyed)	Observed Cache Density (# caches/km surveyed)
1940	0.13	0.18	
1948	0.37	0.47	
1961	1.04	0.90	1.32
1972	1.37	1.12	0.84
1981	1.87	2.10	2.25
1986	1.73	1.74	1.83
1997	0.81	-0.54	1.23
2003	0.81	-0.63	1.41
2005	0.84	-0.55	0.97

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Figure 1. Study area, Kabetogama Peninsula, Voyageurs National Park, Minnesota.

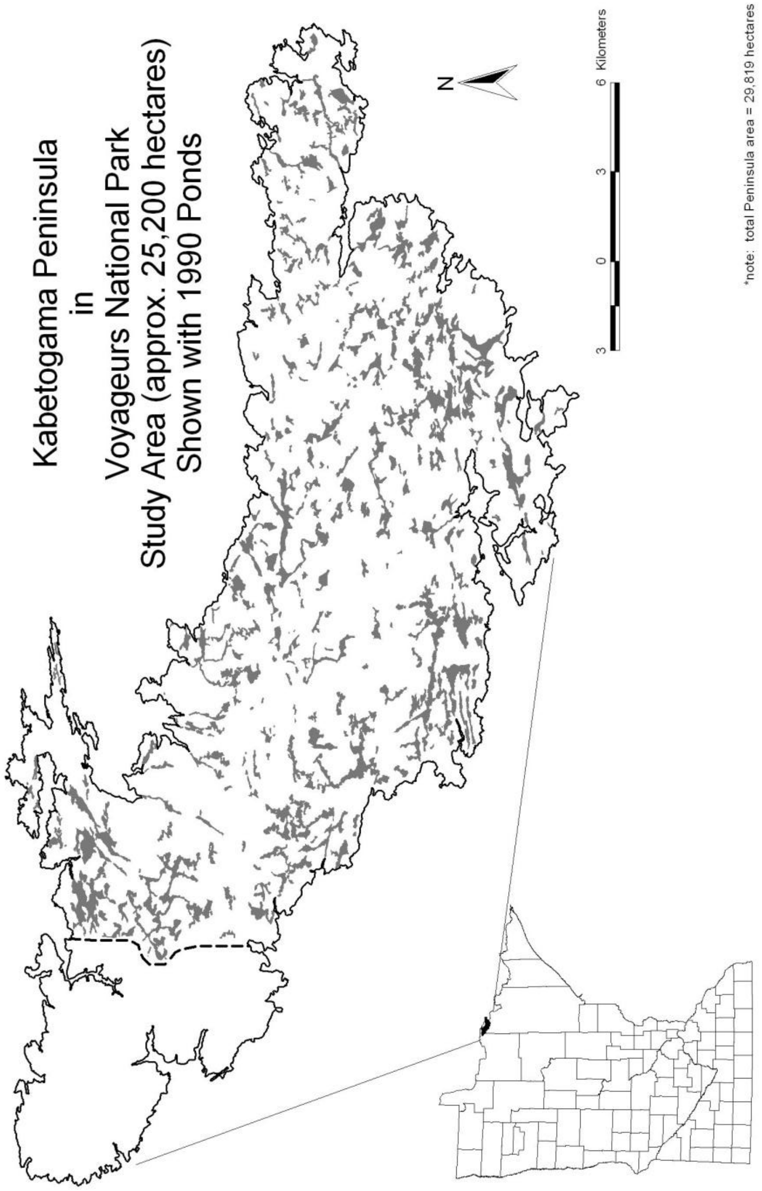


Figure 2. Distribution of plots for the zoom-transfer/ on-screen digitizing comparison study, Kabetogama peninsula, Voyageurs National Park, Minnesota.

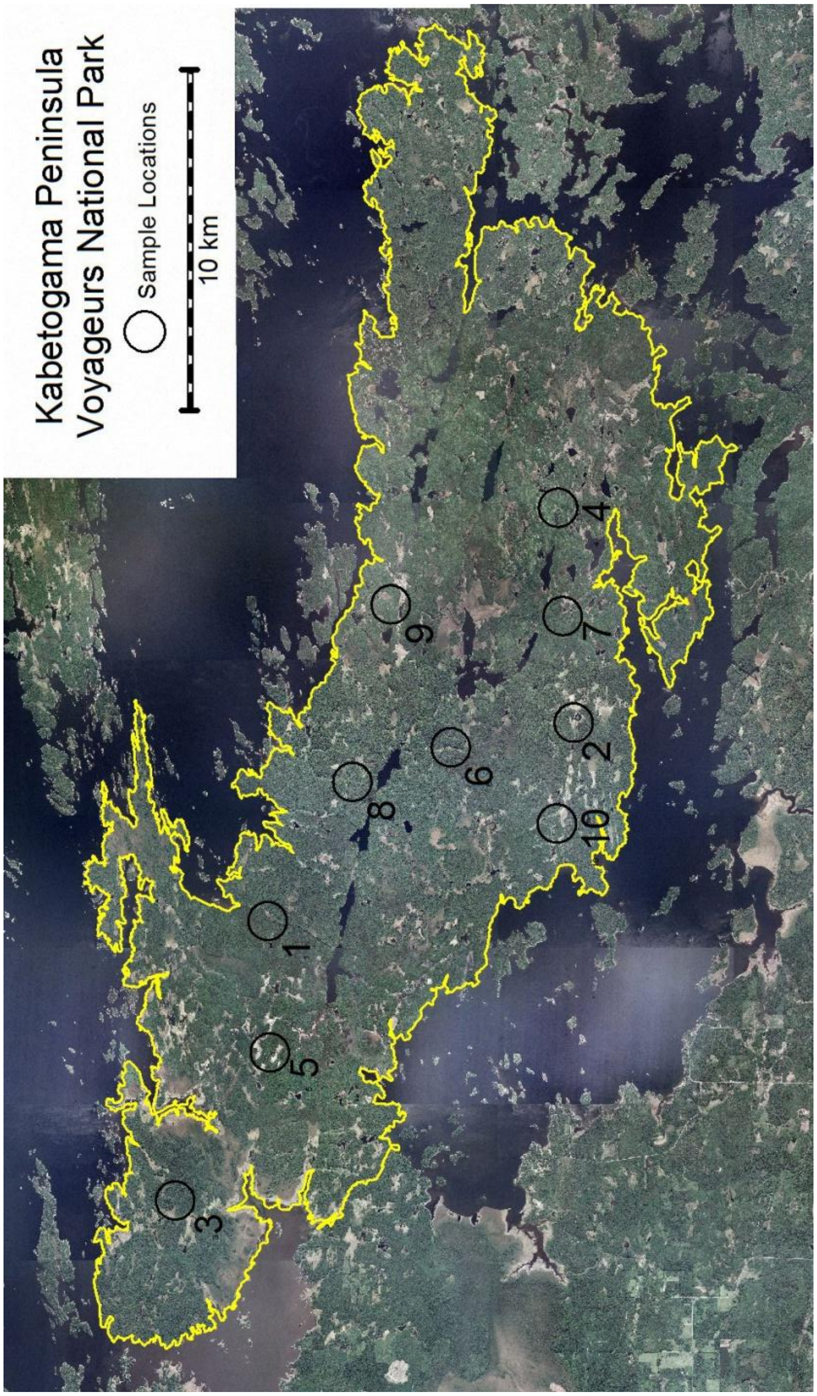


Figure 3. Aerial photographs and impoundment linework from zoom-transfer/onscreen digitizing comparison, plots 1-5.

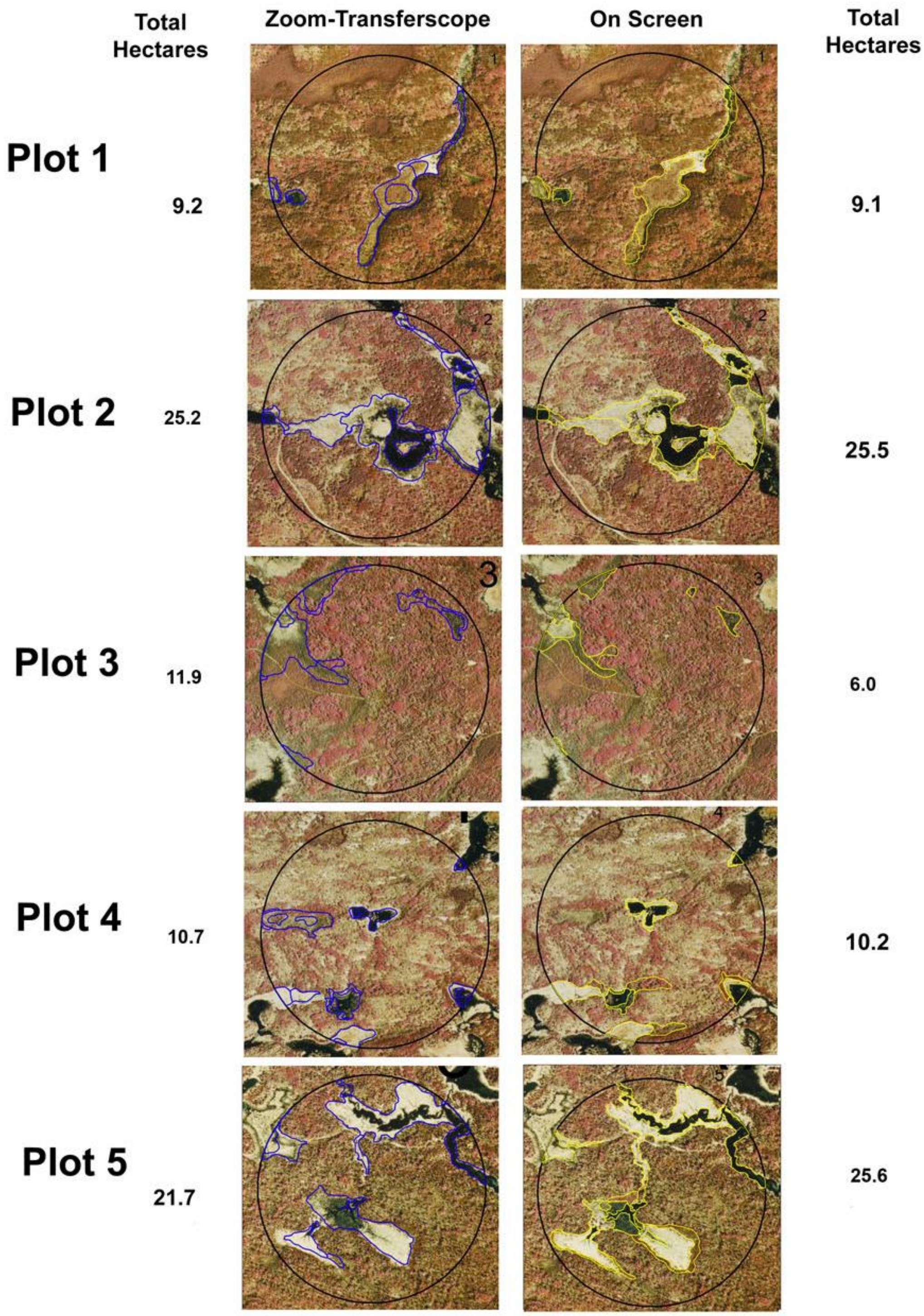


Figure 4 Aerial photographs and impoundment linework from zoom-transfer/onscreen digitizing comparison, plots 6-10.

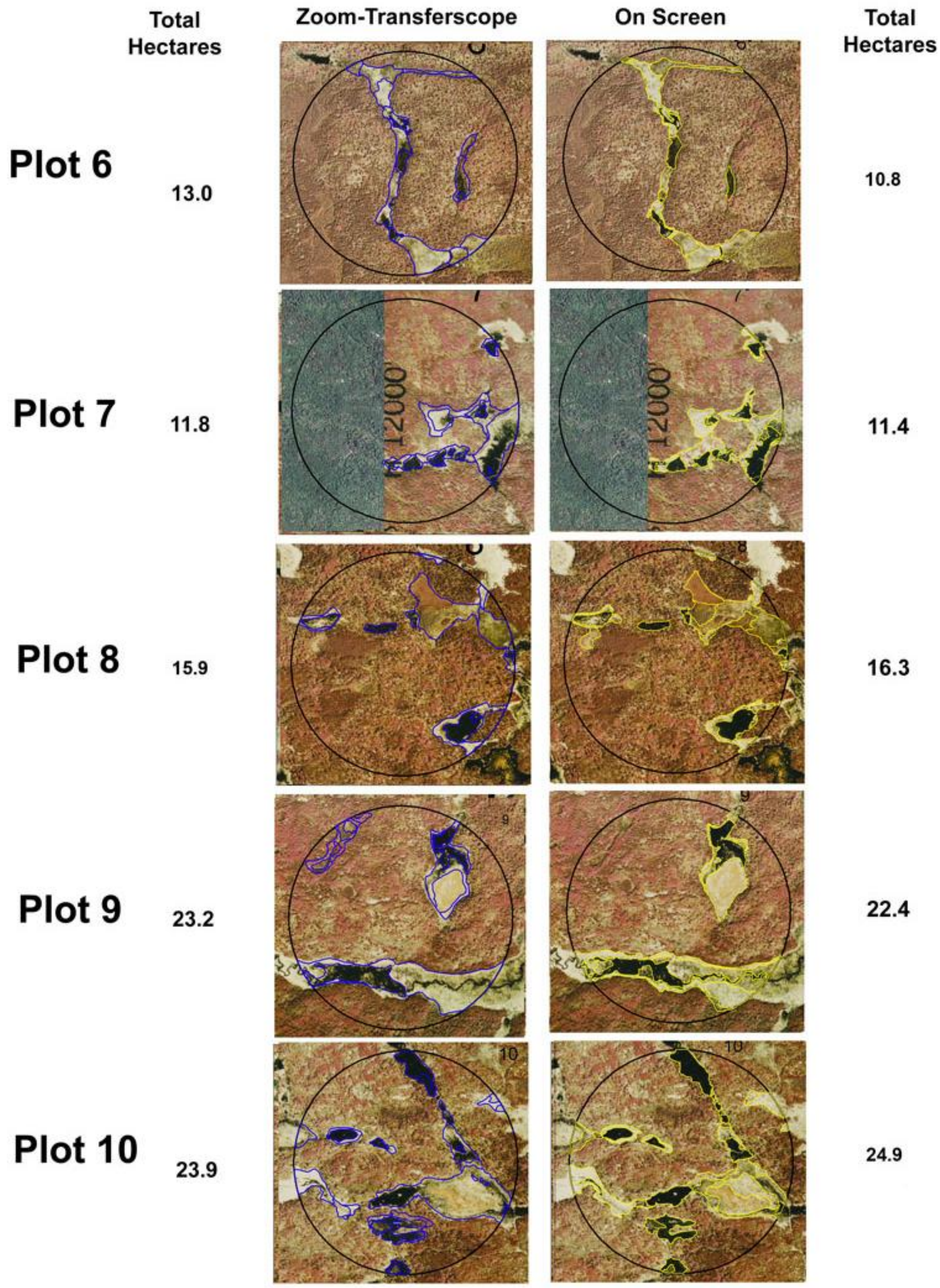
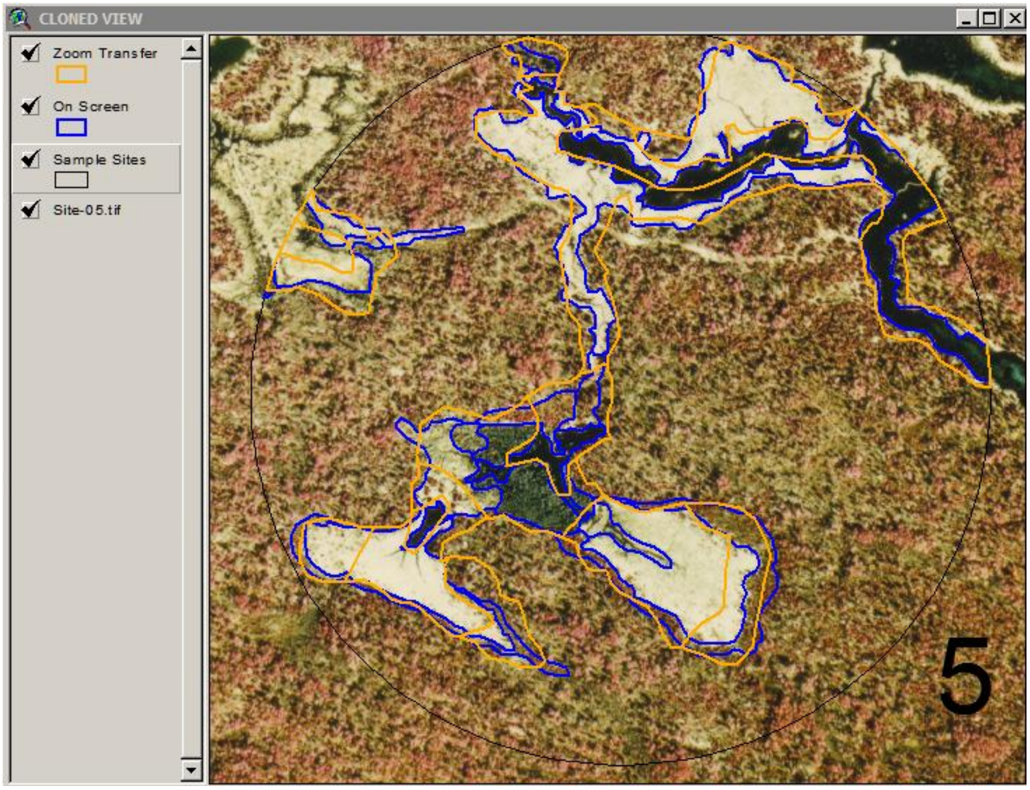


Figure 5. Screen capture of ArcView session from zoom-transfer/onscreen digitizing comparison, Plot 5.



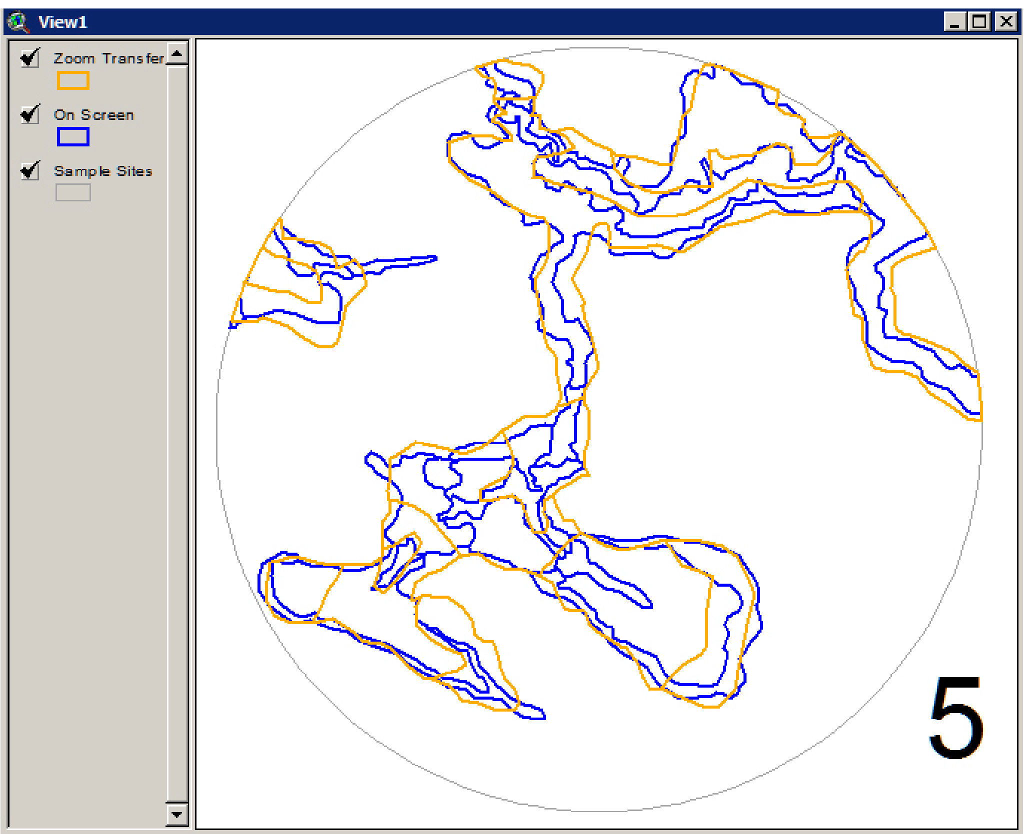


Figure 6. Changes in impoundment area by wetland type, Kabetogama Peninsula, Voyageurs National Park, Minnesota 1940-1986 data from Johnston et al 1990b, 1997-2005 data from present study.

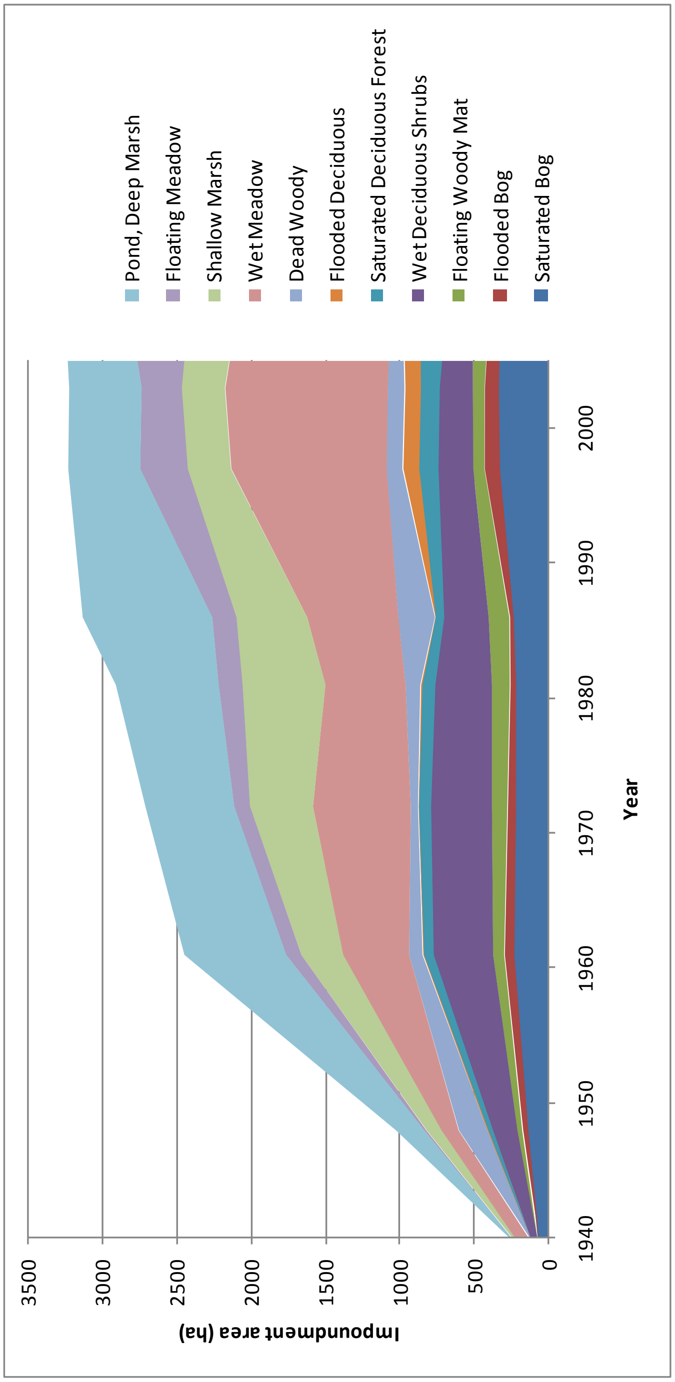


Figure 7. Changes in impoundment area by vegetation class, Kabetogama Peninsula, Voyageurs National Park, Minnesota 1940-1986 data from Johnston et al 1990b, 1997-2005 data from present study.

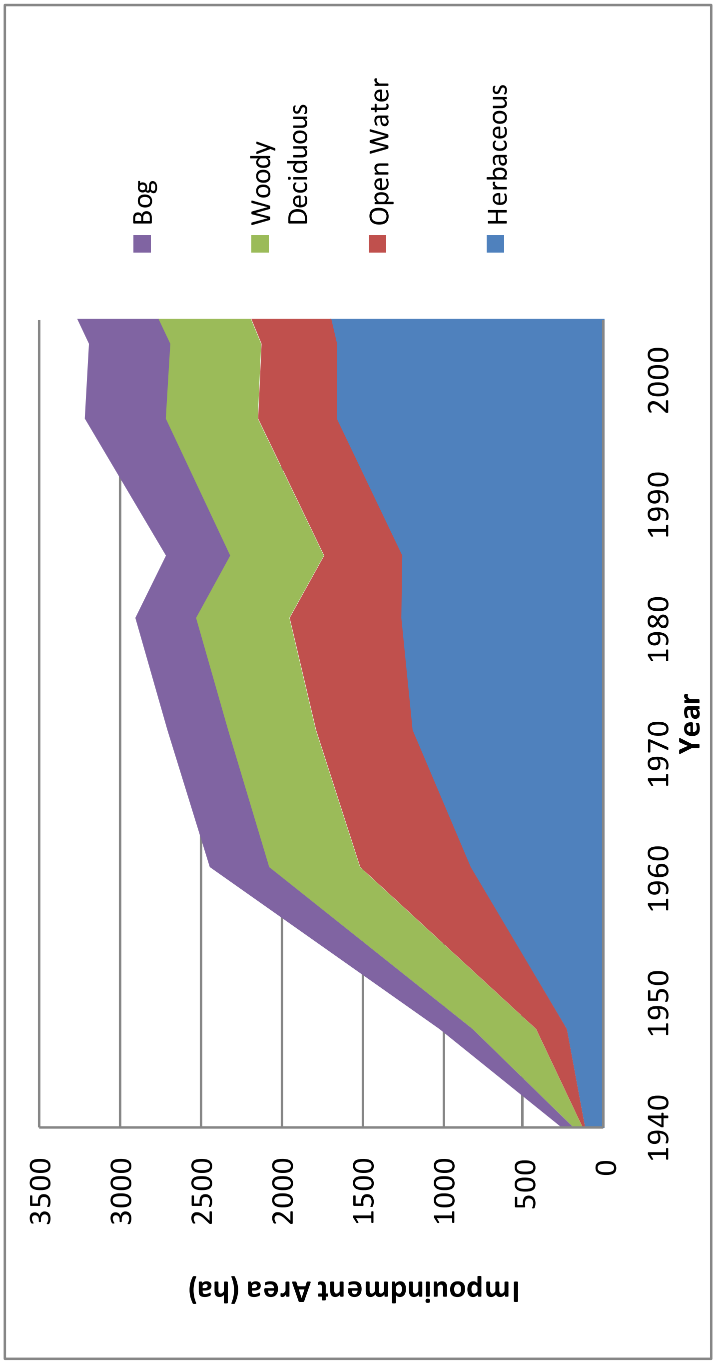


Figure 8 Changes in impoundment area by hydrologic class, Kabetogama Peninsula, Voyageurs National Park, Minnesota 1940-1986 data from Johnston et al 1990b, 1997-2005 data from present study.

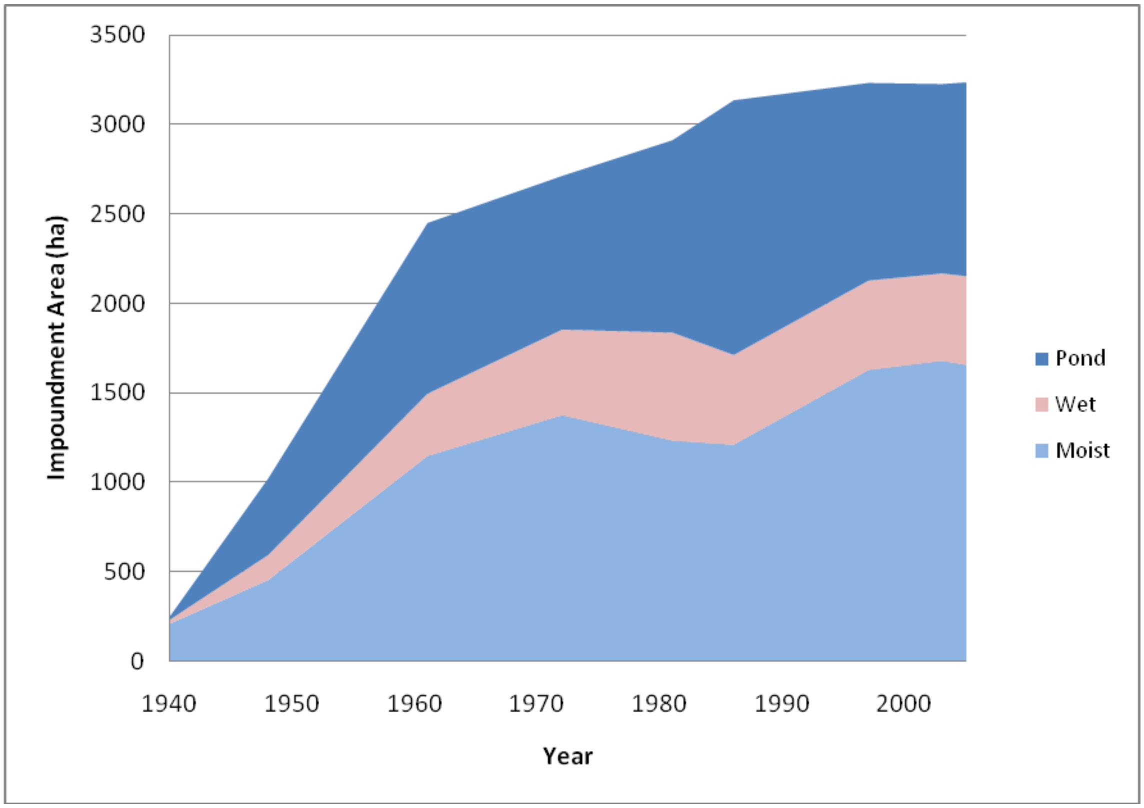


Figure 9 – Spatial distribution of changes in hydrologic class, Kabetogama Peninsula, Voyageurs National Park, Minnesota. 1997-2005.

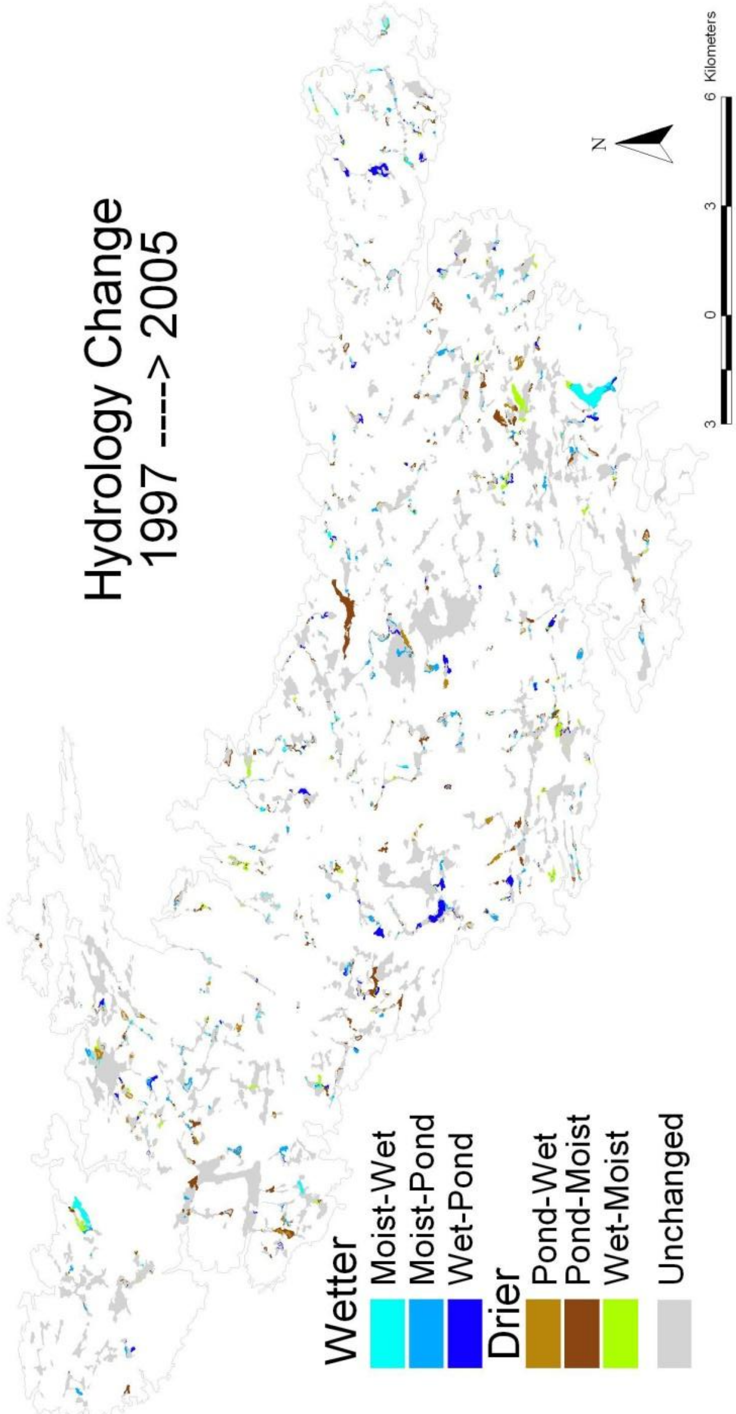


Figure 10. Beaver colony density index (# caches/ km^2 surveyed) from MN DNR aerial surveys, % shallow marsh and deep pond areas relative to total area 1957-2005.

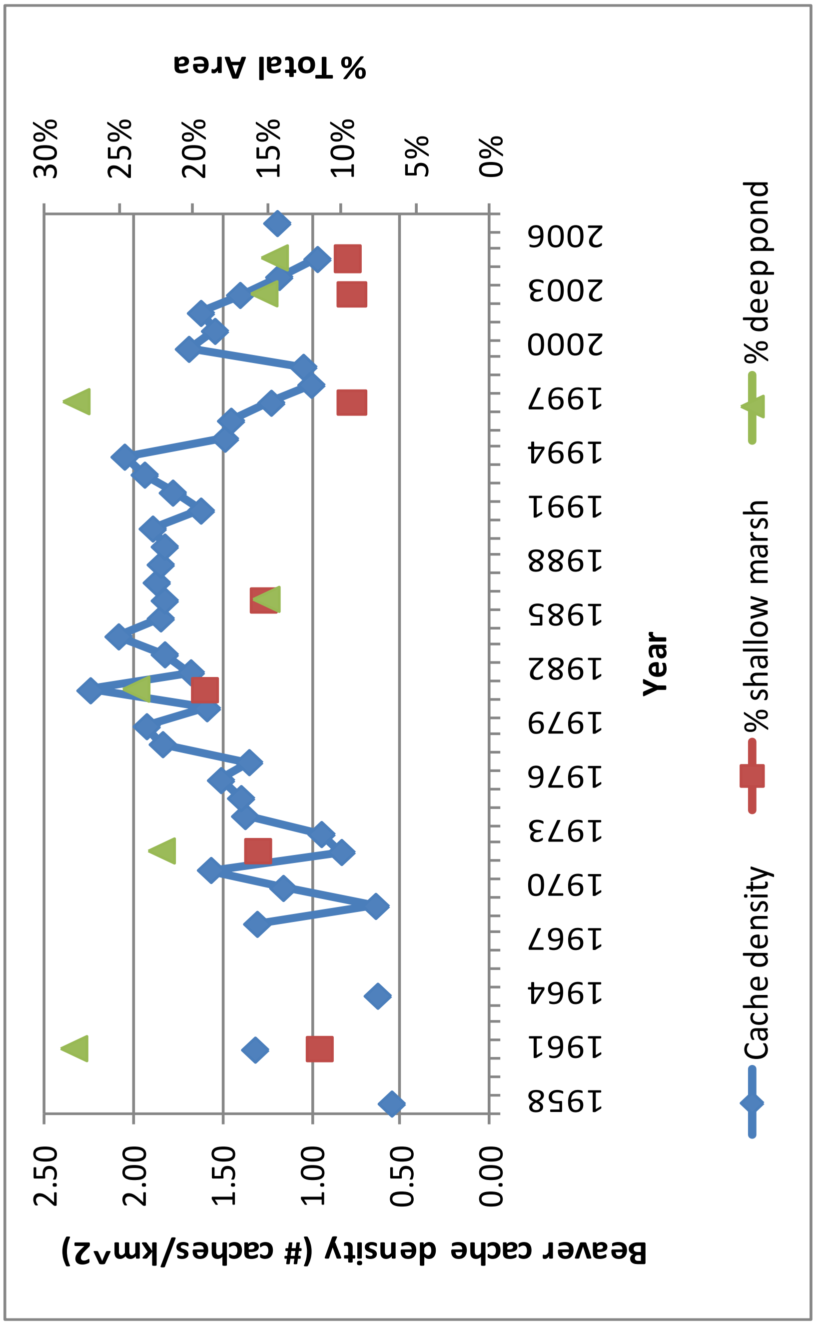


Figure 11. Distribution of caches from aerial surveys in 1984 and 2000, Kabetogama Peninsula, Voyageurs National Park, Minnesota.

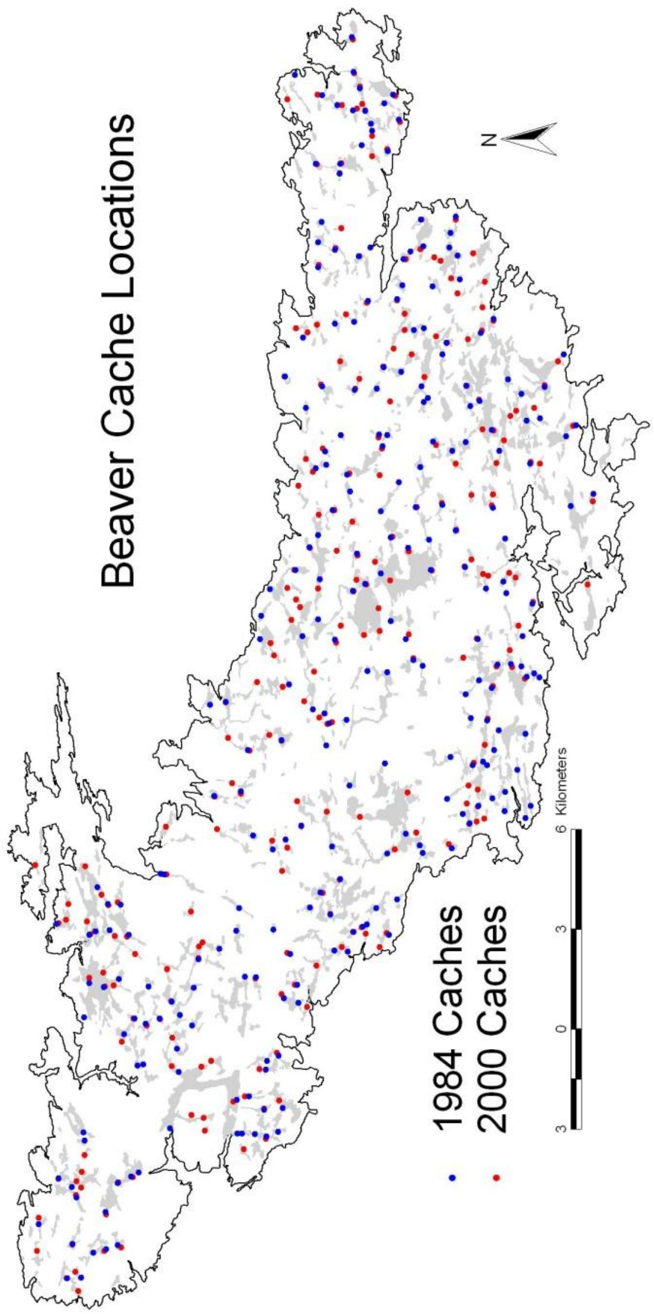
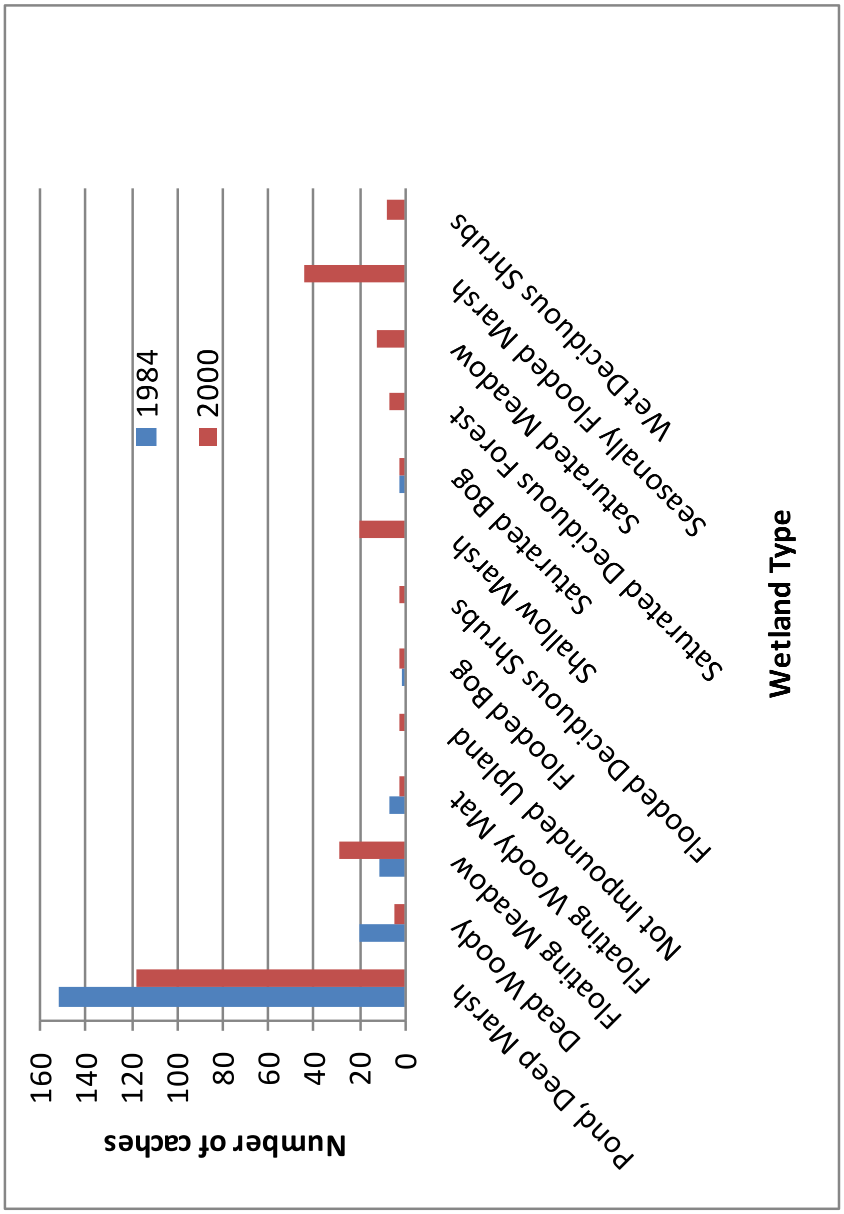


Figure 12. Beaver caches from aerial surveys associated with impoundment types (from 1988 and 2003, respectively.



Appendix A

Beaver Impoundment Delineation and Classification: Considerations for landscape analysis of beaver impoundments and beaver-influenced wetlands in National Parks in the Great Lakes Network

The following summarizes lessons learned from the VNP beaver study that may be relevant to landscape analyses on other National Parks in the Great Lakes Network. It is not intended to be a general guide to photointerpretation or wetland classification, which are well-documented elsewhere, but rather documentation on specific key issues for delineating beaver-influenced wetlands.

Photo acquisition: Many GLKN parks have contemporary and recent aerial photographs, and have or are developing protocols for future image acquisition to monitor changes in land use. Finding and acquiring historic air photos is more challenging.

The majority of the photos used for this project were obtained from the Minnesota DNR. http://www.dnr.state.mn.us/airphotos/index.html. They have contemporary photography available for purchase and have recently added a method to freely download their collection of historic photos - an example seen here:

Newer photography was somewhat easier to process (in our case) due to the simple fact that many more ground control points can be seen. Older photography can be quite challenging to rectify. In rare instances, we had to manually merge the photos in a layer-based graphics program (e.g. Photoshop, etc) prior to the rectification process to obtain a sufficient number of control points. Image editing software provided the ability to use transparency (along with transforming and warping) to line up adjacent photos.

We were fortunate in that we had access to many historic air photo sets from previous work in the area. The St. Louis County Land Department (http://www.co.st-louis.mn.us/slcportal/) was gracious enough to loan some of their photos for processing. Fairly complete sets of the area were taken for logging/timber harvests. Although these were never scanned and rectified, we still had the data sets (polygons, linework, etc) which proved helpful in subsequent photo work.

Voyageurs National Park itself was part of a 1927 international border survey which included air photos.

www.cesu.umn.edu/documents/ProjectReports/MNDNR/MNDNR_NPS_01.Final%20ReportToGLKN.pdf

Again, we were fortunate to obtain these (non-rectified hardcopy photos) for previous beaver study projects.

There are numerous repositories of aerial photography available to the Great Lakes Network. The Minnesota historic air photo collection resides at the John R. Borchert Map Library (http://map.lib.umn.edu/) and their link for image download here: (http://map.lib.umn.edu/mhapo/).

Other state land grant university maintain map libraries, including the Arthur H. Robinson Map Library at the University of Wisconsin Madison (www.geography.wisc.edu/maplib/about.html) and University of Michigan Map Library (http://www.lib.umich.edu/map-library)

Georectification: Georectification of aerial photograph is a key step, allowing the photographs to be viewed in conjunction with other spatial data layers in a common coordinate system.

There are established specified protocols for rectifying aerial imagery in terms of numbers of ground control points and desired accuracy (expressed as maximum RMSE, root mean square error). As a result, it is feasible write a contract for rectifying a large number of photographs according to specified standards. Alternatively, rectification could be accomplished in-house with trained GIS technicians. Software packages for georectification continue to be developed and improved; the VNP project used ArcView ImageWarp, other vendors have comparable software. Hughes *et al.* (2006) provide a good review of accuracy assessment for georectified aerial photographs.

Training: The experience and skill that the photointerpreter brings to the project, particularly the ability to identify beaver structures in wetlands, is significant. At a minimum, we recommend that photointerpreters meet the minimum training standards to conduct interpretations for the National Wetland Inventory. We strongly advise additional hands-on training to photointerpreters moving into the area of beaver pond delineation - as these techniques are not well-codified in the photogrammetric or remote sensing literature.

Data environment: The accurate mapping of beaver ponds and beaver-influenced wetlands is greatly expedited by the concurrent use of multiple spatial data layers while conducting interpretations. These layers include topographic maps, soils and surface water maps, and other wetland inventories. These ancillary datasets to provide references and clues to interpretation, particularly to aid in placement of impoundment boundaries. The GIS environment (in our case, ArcGIS andArcView) provides a considerable advantage over previous methods, allowing overlays and rapid transitions among digital map products such as digital orthophotos (DOQs), digital raster topographic maps (DRGs), rectified photography, and polygon or raster coverages of previous work. Interpretations of previous impoundments are an important data layer when available; the fact that beaver-influenced wetland was delineated in a previous episode requires that this area be re-evaluated for changes in impoundment type or size.

Delineations: The methods for delineating wetlands from aerial photography and incorporating these in to spatial databases are well-developed, by both federal and state agencies – particularly noteworthy are the procedures developed by the US Fish and Wildlife service (www.fws.gov/wetlands/_documents/gNSDI/DataCollectionRequirementsProcedures.pdf) as guidelines for the National Wetland Inventory. Active and recent beaver impoundments have obvious physical features - the presence of beaver lodges and dams – that, with training, are readily detected by an airphoto interpreter; some examples are provided below.

The original VNP beaver study was possible because of the availability of a time sequence of aerial photographs that allowed the development and decline of beaver impoundments to be quantified. It is likely that many other parks have similar sequences of historic air photographs, allowing these analyses to be replicated. In fact, conducting this analysis in a single interpretation episode will avoid potential problems associated with different interpreters, different times and different technologies.

GIS Tools: As noted above, delineating beaver impoundments can be enhanced by using ancillary data layers. Previously Arc users would toggle data layers on and off – ArcGIS now provides the ability to 'sweep' data layers on and off, providing a high degree of precision in reviewing a small area onscreen. It is particularly useful to compare photos from different dates, this allows the user to detect changes in impoundment boundary or type. The following images provide examples of using multitemporal images in the detection process.

Example 1: It might not have been possible to determine that this area was a beaver pond without the corresponding clues provided by the 1997 photo. A large beaver lodge (point "A") and also a newer small lodge (point "B") are evident in the 1997 photo. The points labeled "C" identify the dams that are visible in the newer photo. This particular pond would be classified as Cowardin class 10 (UBF, open water pond, deep marsh) in 1997 but the major part of this area "D" in 2003 would be classified as saturated meadow (EM1A or EM1B) and "E" seasonally flooded marsh (EM1E).

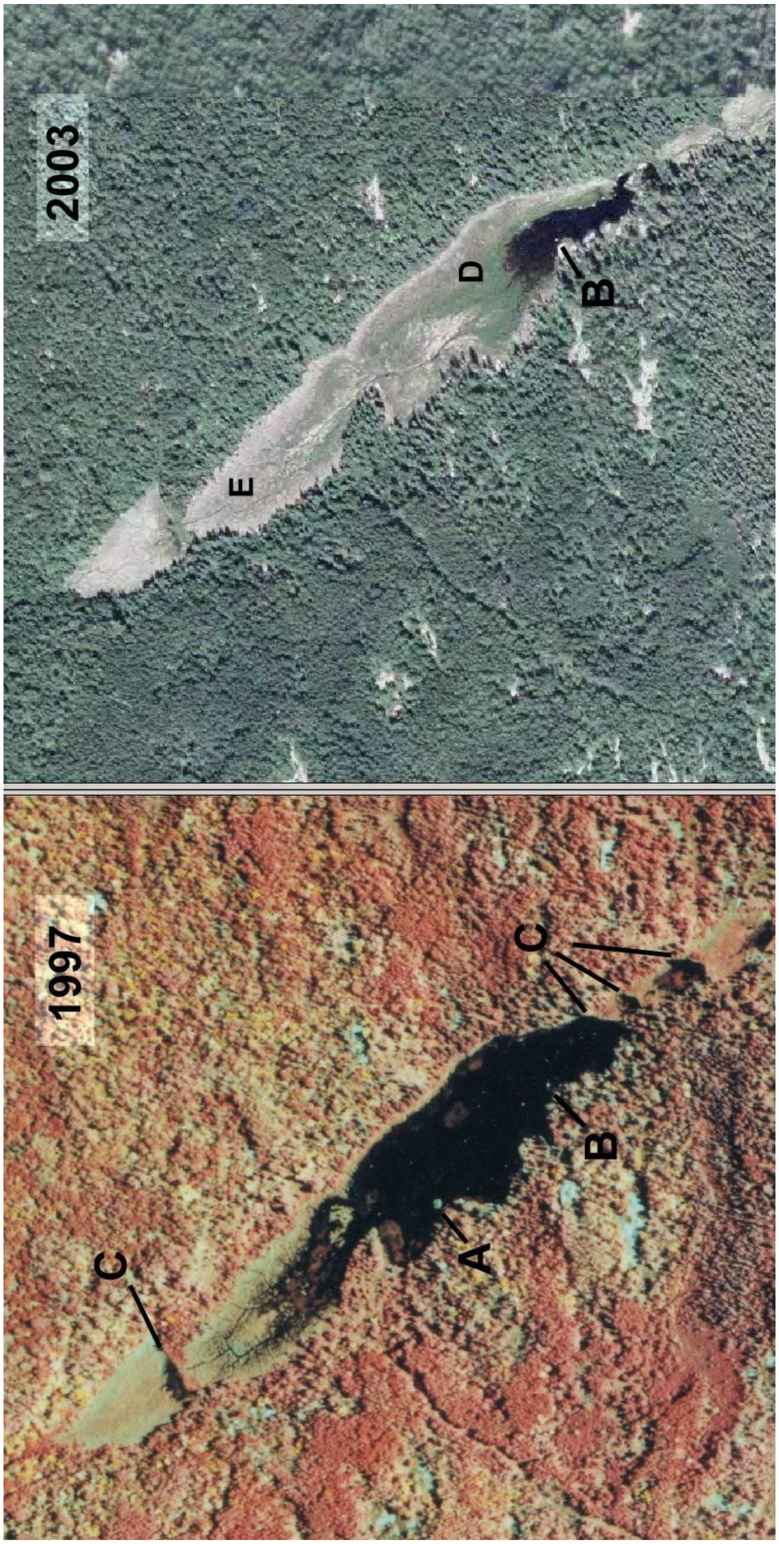


Figure 1. Illustration of use of previously classified beaver impoundments to inform interpretation of subsequent imagery.

Example 2: The locations marked "A" indicate the main beaver lodges which can be seen at this photo resolution. Locations "B" indicate the large, main (about 90 m long) beaver dam which indicates 2003 beaver activity above the dam. Below (downstream) this large dam the lower pond has collapsed and significantly changed the landscape. This collapse accounts for a significant decrease in the open water. At locations "C" we can see two smaller ponds which have collapsed - in the case of the more northerly one, there is no evidence of current beaver activity at this time.

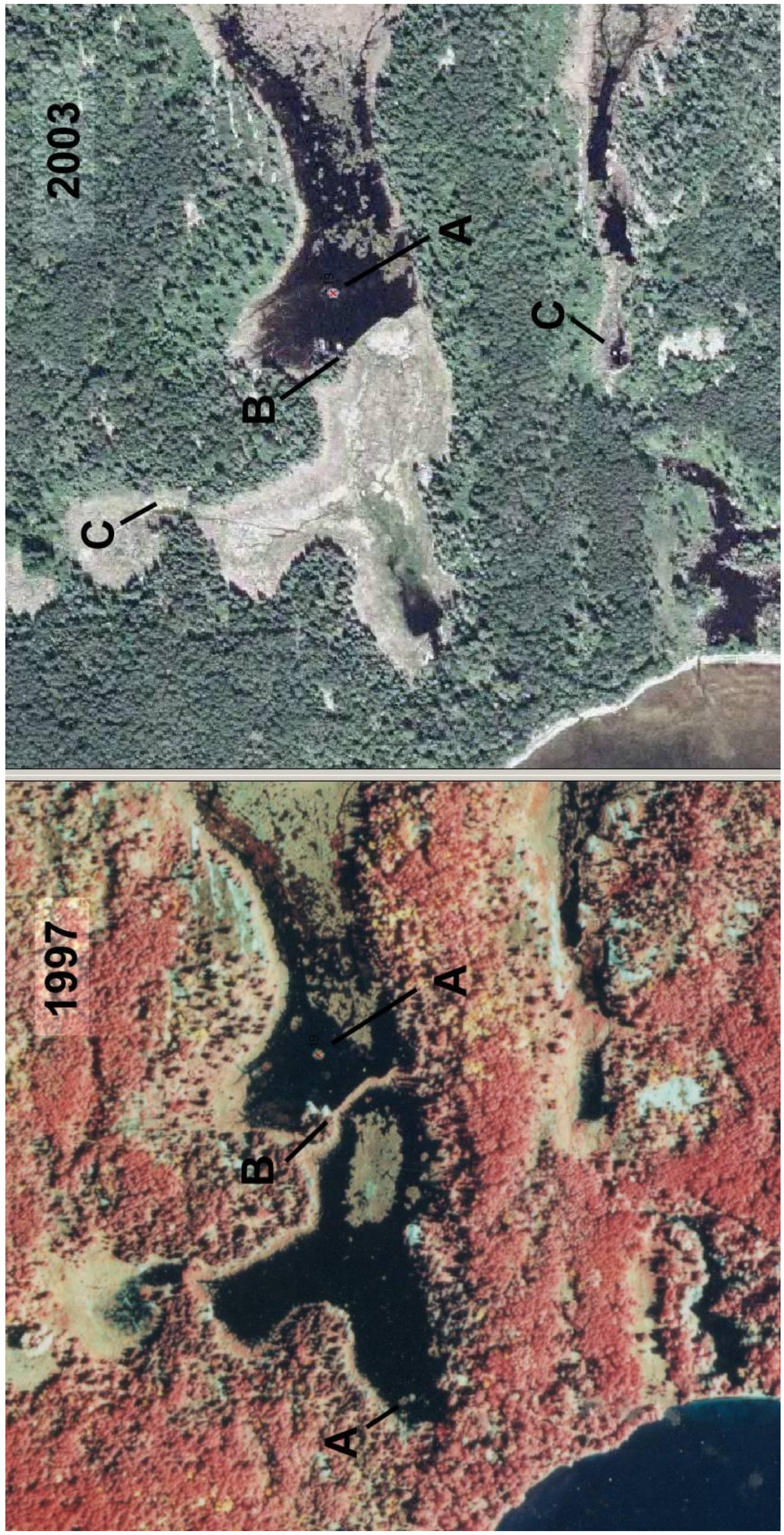


Figure 2. Illustration of landscape change following collapse of beaver dams.

Without historic data, this process of determining beaver-influenced ponds and wetlands would be much more difficult. The ability to compare these images onscreen using the ArcGIS sweep utility greatly simplifies the interpretation process. To more easily map the succession of impoundment types over time, sets of historic photos should be analyzed in chronological order.

Metadata: Maintaining appropriate metadata is always important, but particularly important in managing multitemporal data sets. Care should be taken that shapefiles from different years use common field names. All data should meet, at a minimum, standards of the Federal Geographic Data Committee (FDGC; www.fgdc.gov/standards/).

Reference

Hughes, M. L., P. F. McDowell, and W. A. Marcus. 2006. Accuracy assessment of georectified aerial photographs: implications for measuring later channel movement in a GIS. Geomorphology 74:1-16.